# Hubble Space Telescope Science Metrics

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## ABSTRACT

Since its launch in April 1990, the Hubble Space Telescope (HST) has produced an increasing flow of scientific results. The large number of refereed publications based on HST data allows a detailed evaluation of the effectiveness of this observatory and of its scientific programs. This paper presents the results of selected science metrics related to paper counts, citation counts, citation history, high-impact papers, and the most productive programs and most cited papers, through the end of 2003. All these indicators point towards the high-quality scientific impact of HST.

*Subject headings:* Telescopes:(Hubble Space Telescope)

## 1. Introduction

The Hubble Space Telescope (HST), orbiting the Earth at an altitude of about 600 kilometers, is the product of an international collaboration between the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). Its position high above any atmospheric turbulences and the quality of its instruments provide the astronomical community with observation of excellent resolution and sensitivity in the wavelength domains of the ultra-violet, visible, and near infrared.

HST has produced an increasing flow of scientific data since its launch by the Space Shuttle Discovery, in April 1990. After more than a decade of Hubble observations, the large number of publications based on HST data provides a statistically sound basis to determine the scientific effectiveness of this observatory.

There are numerous previous studies about science metrics in astronomy : Abt (1981) studied the behavior of citation histories for papers published in 1961. Trimble (1995) analyzed papers and citation counts for papers based on data collected at large telescopes. Benn & Sánchez (2001) estimated the participation of different facilities in the most cited papers in astronomy from 1991 to 1998. Crabtree & Bryson (2001) examined in detail the productivity and impact of the Canada-France-Hawaii Telescope (CFHT).

Improvements in databases for paper and citation counts have prompted the Space Telescope Science Institute (STScI) to develop a new standard methodology to define the scientific impact of HST through quantitative and objective metrics. The aim is twofold: (i) to monitor the use of the telescope in order to improve and maximize its scientific output through adjustments in the process of the allocation of observing time, and (ii) to report to the funding agencies, to the various governing committees, and to the astronomical community. See Meylan et al. (2003) for a succinct presentation of some of our metrics results.

There are two straightforward and relevant measures of the effectiveness of a telescope: the number of refereed papers based on data obtained by the telescope, and the citation count for those papers. It is obvious that the full scientific impact of a facility may also be evaluated through other metrics, such as the number of press releases, the "most important" discoveries, etc. The aim of this paper is to show the results of the first two met-

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rics (paper and citation counts), both objective quantities which could be reproduced and verified by other authors.

The content of this paper is the following: Section 2 describes the way we search and identify refereed papers using HST data, Section 3 presents the statistics on the numbers of papers and their citations, Section 4 defines and discusses the so-called High Impact Papers. Sections 5 and 6 present some highlights of the science produced by HST through the top ten most productive programs and top ten most cited HST papers. This paper is devoted to HST publications only; comparisons with other telescopes will be done in the near future through collaborations with those facilities.

## 2. Identification process of Refereed Papers Using HST Data

There have been various definitions of what constitutes "a paper based on HST data". Some of these definitions require that, of the total amount of observational data used in a paper, at least 50 % of them originate from HST. Others do not include papers based on archival data. Since it is impossible to define precisely and consistently the fraction of HST data used in a given paper, we adopt the simplest possible definition: "a paper based on HST data" is a paper benefiting directly from HST observation. Such a paper must contain at least: an HST image, an HST spectrum, or new numbers derived directly from HST data. All papers based on data retrieved from the HST archives are included. We take into account papers using archival data either for reanalysis or for new scientific aims. This broad definition has also been adopted by other observatories (e.g. ESO), but it has to be clearly stated if the numbers are to be used for comparisons amongst different facilities, which is not our aim in this paper.

Most of the information we use comes directly from the ADS, the NASA Astrophysics Data System hosted in Cambridge, USA, at the Harvard-Smithsonian Center for Astrophysics (see Kurtz et al. 2000).

We run a boolean logic query on the ADS with the following search string: "HST OR (HUBBLE AND SPACE AND TELESCOPE) OR WFPC OR WFPC1 OR WFPC2 OR (WF AND PC AND HST) OR (WIDE AND FIELD AND PLANETARY AND CAMERA) OR FGS OR (FINE AND GUIDANCE AND SENSORS) OR HSP OR (HIGH AND SPEED AND PHOTOMETER) OR FOC OR (FAINT AND OBJECT AND CAMERA) OR FOS OR (FAINT AND OBJECT AND SPECTROGRAPH) OR HRS OR GHRS OR (GODDARD AND HIGH AND RESOLUTION AND SPECTROGRAPH) OR STIS OR (SPACE AND TELESCOPE AND IMAGING AND SPECTROGRAPH) OR NICMOS OR (NEAR AND INFRARED AND CAMERA AND MULTI AND OBJECT AND SPECTROMETER) OR ACS OR (ADVANCED AND CAMERA AND SURVEYS)".

The above query produces a list of papers, with sometimes wrongs hits (HST stands also for Hawaiian Standard Time!). Each paper is, then, downloaded and read in order to confirm whether it is a genuine HST paper. Since the ADS allows to query only the abstract of a paper and not its full text, hard copies of all refereed journals are searched manually by the staff of the STScI Library.

For each identified HST paper, we search for the program(s) ID(s) of the HST data used. A link is then established in MAST, the Multimission Archive at Space Telescope, between the paper and the program(s). There is at least one program ID for each HST paper. For each HST program, the list of publications that it has generated is accessible on-line to the astronomical community through the MAST website `http://archive.stsci.edu/hst/search.php` by entering the proposal-program ID.

Our list of papers recognized as using HST data is publicly available on-line and can be accessed by the astronomical community through the ADS at `http://adsabs.harvard.edu/`, by activating the HST filter under `select references in`. Each month, the ADS receives from MAST, our updated list of publications, in an automatic and electronic way.

It is worth mentioning that the amount of work required to identify a paper and link it to a program is, sometimes, very onerous. We have encountered many stumbling blocks, often created when authors provide the wrong program IDs. We have even identified a few papers which wrongly claimed to be based on HST data.

In order to test the completeness of our list of refereed papers, we contacted all of the PIs of programs in Cycles 4 and 5 for which we could not find any refereed publications arising from their data and the PIs confirmed that there were no additional papers. However we expect that a few papers may have been missed by our search, but the number must be very small, certainly less than a few percent.

## 3. Paper and Citation Counts Metrics

Most of the HST refereed papers (about 90 %) are published in the five major refereed journals, viz., the Astrophysical Journal (ApJ), the Astronomical Journal (AJ), Astronomy and Astrophysics (A&A), the Monthly Notices of the Royal Astronomical Society (MNRAS), and the Publications of the Astronomical Society of the Pacific (PASP). We, of course, also count all papers in the other refereed journals, such as Nature and Science. In this paper, we take into account only refereed publications published by the end of December 2003.

### 3.1. Paper Counts per Year

The number of refereed papers based on HST data is given in Fig. 1 as a function of the year of publication. Hubble is an extremely productive telescope: between its launch in April 1990 and the end of 2003, it has produced data directly used in 4,116 refereed papers. Following a strong and regular increase of publications during the first eight years, the number of papers continued to increase, although at a slower pace, during the last five years, to reach a value of 502 for the year 2003.

The percentage of HST papers published in the aforementioned five major journals, has grown from 1% in 1991 to 7% in 2003. Some special issues of the Astrophysical Journal have been dedicated to HST papers only: the first such issue was published in March 1991 with data from the first generation of instruments, while the last such issue, devoted to papers based on data from the Advanced Camera for Surveys (ACS), appeared in January 2004 (the papers in the latter issue are not included in this study).

Fourteen years after its launch, HST continues to have an increasing productivity, which can be explained by the regular servicing missions that maintain state-of-the-art technology for its scientific instruments and spacecraft systems. The rate of production of refereed papers reflects the increase in the "discovery space" provided by the new scientific instruments deployed in each servicing mission.

### 3.2. Paper Counts per Cycle

The numbers of refereed papers published per year for all the programs of a given cycle provide an interesting metric. Fig. 2 presents such information for Cycles 1 and 2, Cycles 3 and 4, Cycles 5 and 6, and Cycles 7 and 8.

In the upper-left panel (Cycles 1 and 2), the initial increase of productivity during the first 3-4 years culminates in a peak, which is followed by a slow decrease. Then, the productivity stabilizes at a level of about 20-30 papers per year, 10-12 years after the beginning of these cycles.

In the upper-right panel, there is an obvious major difference between Cycles 3 and 4. The high productivity of Cycle 4 when compared with Cycle 3 is a direct consequence of the first servicing mission which corrected the spherical aberration of the primary mirror with the installation of new

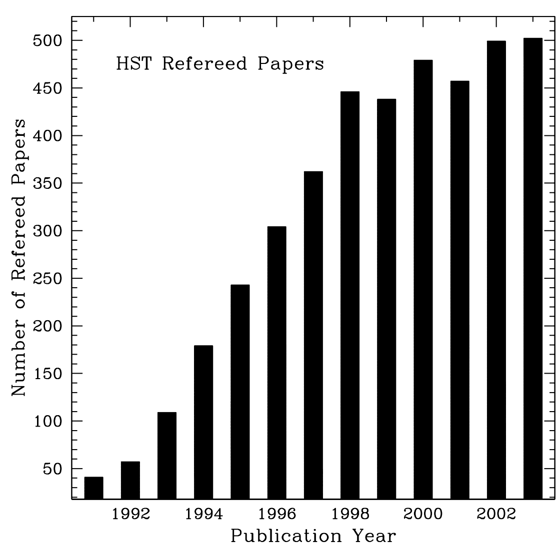


Fig. 1.— Numbers of refereed papers based on HST data as a function of the year of publication.

instruments. The significant increase in data quality triggered a burst in publications using the significantly improved performance.

This high level of scientific output has continued to increase since then, as shown in Fig. 2 lower-left panel for Cycles 5 and 6 and lower-right panel for Cycles 7 and 8. Each cycle has a peak in productivity of about 180 papers reached about 3-4 years after its beginning.

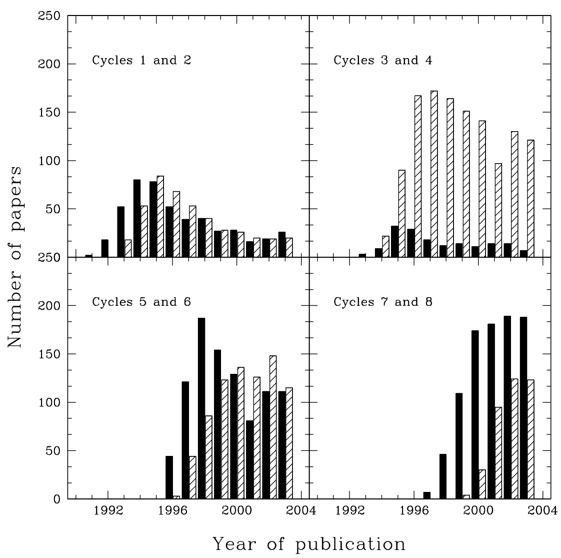


Fig. 2.— For Cycles 1 (solid-black histogram) and 2 (cross-hatched histogram) programs, numbers of refereed papers based on HST data as a function of the year of publication are plotted on the upper-left panelbox. Idem for Cycles 3-4, 5-6, and 7-8.

### 3.3. Paper Counts per Instrument

Fig. 3 gives the number of refereed papers published per year based on data from each Hubble instrument. The number in each panel is the time integral of the corresponding curve. FGS stands for Fine Guidance Sensors, FOC for Faint Object Camera, STIS for Space Telescope Infrared Spectrograph, GHRS for Goddard High Resolution Spectrograph, HSP for High Speed Photometer, NICMOS for Near Infrared Camera and Multi-Object Spectrograph, FOS for Faint Object Spectrograph, WFPC and WFPC2 for the first and second Wide Field and Planetary Camera, and the ACS for Advanced Camera for Surveys. The FOC, GHRS, HSP, FOS, and WFPC are decommissioned instruments, while FGS, STIS, NICMOS, WFPC2, and the ACS are active. A paper may be counted more than once if the data it uses come from more than one instrument.

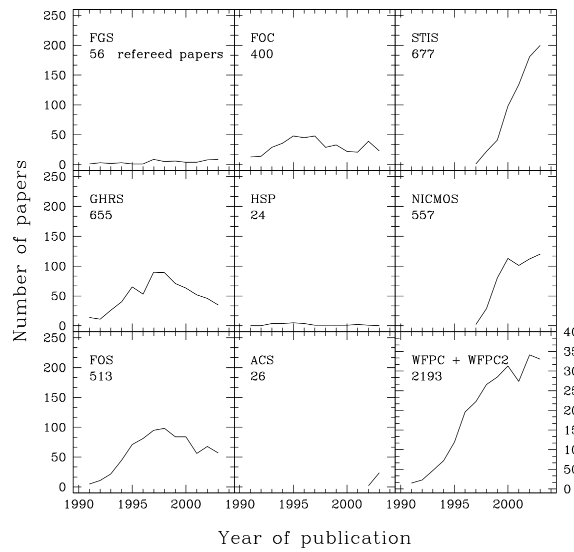


Fig. 3.— Number of refereed papers based on HST data as a function of the year of publication, from launch to the end of 2003, for active and decommissioned HST instruments. The total number of papers in this figure is 5101, a value larger than 4116, the total number of HST refereed papers. This is due to the fact that about 1000 papers use data from more than one instrument and are counted more than once.

### 3.4. Archives as an Instrument

By definition, we consider as an archival HST paper, any paper which fulfill simultaneously the following two conditions: (i) it is based on HST data retrieved from MAST, the Multimission Archive at Space Telescope, and (ii) none of its authors is neither a PI nor a CoI on any of the HST programs from which these data originate.

Software tools able to identify such papers have been developed only very recently. We currently have an estimate of the fraction of archival HST papers only for the years 2000 through 2003. Out of the 1870 HST papers published during these

four years, 654 are archival HST papers. This amounts to 34 % of the HST papers (K. Levay and MAST team 2004, private communication).

### 3.5. Citation Counts per Year

To estimate the scientific impact of the refereed papers based on HST data, we obtain from the ADS the total number of citations for each paper in our databases.

The ADS itself is well aware that its citation counts may suffer from some (small ?) incompleteness. However the ADS constantly improves its products and represents the most reliable source of citations for papers published in the major astronomical journals. The ADS has two essential advantages: is it available on-line and free of any charge. We use, on a weekly basis, a script provided by the ADS, which allows us to access directly the total number of citations for each paper in our databases.

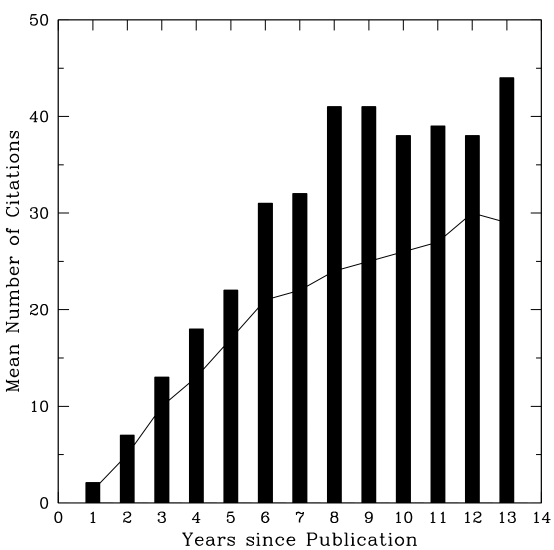


Fig. 4.— Mean number of citations of refereed papers based on HST data as a function of the years since publication. The solid curve represents the mean numbers of citations for all astronomy.

The Institute for Scientific Information (ISI), based in Philadelphia, sells citation counts, which after a few checks, appear not more reliable than those from the ADS. Sandqvist (2004) presents a few examples of large differences between the ISI and the ADS because of errors made by the ISI. Stevens-Rayburn & Bouton (2002) also discuss disparities of citation counts for the two providers.

For Fig. 4, we consider only papers in the five major journals (ApJ, AJ, A&A, MNRAS, and PASP), since other journals, such as Nature and Science, would bias our statistics with their numerous highly-cited articles not related to astronomy. The histogram in Fig. 4 displays the mean total number of citations of refereed HST papers as a function of years since publication. For the older papers, published between 7 and 12 years ago, the mean total number of citations is about 40 per paper, and is smaller for more recently published papers. The segmented line in this figure shows the mean total numbers of citations, for all astronomy papers in the aforementioned five major journals. The refereed HST papers have an average number of citations per paper larger (by at least 25%) than the average number of citations of all the astronomical papers.

Fig. 5 shows that, a few years after publication, only about 2% of the refereed HST papers have no citations, whereas about one quarter of all refereed papers in astronomy have no recorded citation in the ADS.

These two figures show that the refereed HST papers have a scientific impact significantly above average.

### 3.6. Citation History

The citation counts allow the study of the evolution of citation rates of papers as a function of the years following publication. Such metrics allow to answer the following questions: How fast is the growth in citation rate ? Is there a maximum citation rate ? After how many years is this maximum reached ? How fast is the decline in citation rate ?

We have obtained the individual citations of all the 4,116 refereed HST papers, courtesy of the ADS (Kurtz, 2003a). This amounts to a total of 64,141 citations. Fig. 6 presents the average citation counts per paper as a function of the number of years since publication. The continuous line is the average for the HST papers, while the dashed line is the average of all refereed papers in astronomy.

In both cases after a sharp rise, the peak of

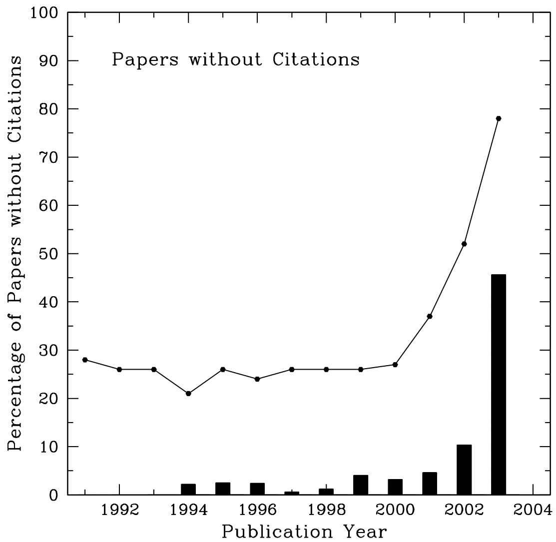


Fig. 5.— Percentage of refereed HST papers without citations as a function of the year of publication, as solid-black histogram. The solid curve represents the percentage of refereed papers without citations for all astronomy.

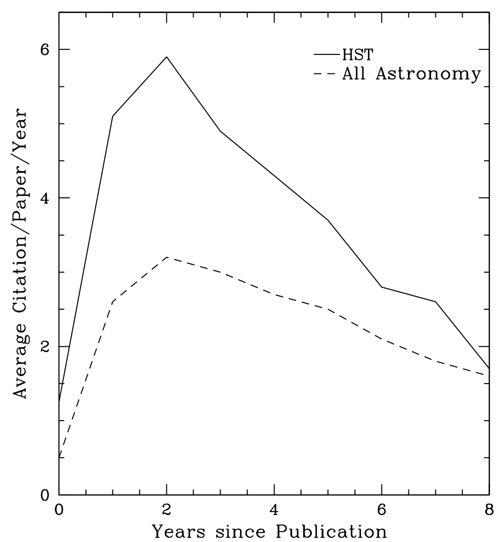


Fig. 6.— Citation history: average citations rate per paper per year. The continuous curve represents the average for the refereed HST papers, while the dashed curve represents the average for all astronomy papers.

the citation rate occurs approximately two years after publication. HST refereed papers peak at an average of 5.9 citations/paper/year, while the peak reaches only 3.2 citations/paper/year for all refereed papers in astronomy. Thereafter, the citation rate decreases linearly to be about 2 citations/paper/year ten years after publication.

Crabtree & Bryson (2001, 2002) generated similar curves for the papers produced from observations by the Canada-France-Hawaii Telescope (CFHT) and the UK Infra-Red Telescope (UKIRT). Their curves peak at about 4.0 - 4.5 citations/paper/year, and display the same general shape; a sharp rise, a maximum reached after two years, followed by a slow decline. Abt (1981) showed that for papers published in 1961, citations reach a maximum five years after publication. The delay between publication date and the peak of citations has shortened since that time to an average of two years. This may be a direct consequence of the strong increase, during the last decade, in the spread of information through the World Wide Web.

### 3.7. ADS 2000-2001 reads of papers

For each paper, each access through the ADS generates a log entry, which is called a “read”. An independent and new way of measuring the readership of a paper is the number of “reads” it generates (Kurtz, 2003b). Michael Kurtz of the ADS kindly provided us with data related to this new metric.

During the two years 2000 and 2001, the ADS recorded about 12 million reads of all astronomy papers, out of which 10 million were related to refereed papers. At that time, the then 3113 HST refereed papers accumulated 533,362 reads during these two years, corresponding to 5.3% of all reads of astronomy papers.

## 4. High Impact Papers

There is more than one way to identify papers which have a high scientific impact. An interesting metric is given by the papers which have the largest numbers of citations: called High Impact Papers (HIPs) by the ISI (see http://www.isinet.com/rsg/hip). We adopt the

ISI definition: a paper is a HIP if it belongs to the 200 most cited refereed papers published in a given year. The ADS has the capability to sort all papers by citation counts and publication dates. It is straightforward, from the ADS, to obtain the top 200 papers published in a given year.

We identify the HST refereed papers which have enough citations to be among the HIPs published in a given year. Fig. 7 provides the percentage of HIPs based on HST data as a function of publication year. After a slow start in 1991, 1992, and 1993, the effect of the successful deployment of COSTAR and WFPC2 on the impact of refereed papers is obvious between 1993 and 1994. Since 1994, Hubble has consistently generated about 8% of all HIPs.

We have extracted the High Impact Papers for the following four years: 1998, 1999, 2000, and 2001, and studied in greater details these 800 papers. Namely, for each paper we accessed the full text using the ADS, read the paper and decide whether it is an observational or theory paper. Hereafter we consider only observational papers. If, for a paper, there is more than one telescope providing the observations, the weight or percentage of the contribution coming from each facility is roughly estimated (e.g., 50 % HST, 25% Keck, and 25% Chandra), and the citations of this paper are attributed to the facilities as a function of these percentages. In this way, the total number of citations related to the 200 HIPs of a given year is distributed among all telescopes/facilities that provided the data.

Table 1 gives the distribution of the citations of the 200 HIPs published in 1998 as a function of the most highly cited facilities (we display here only the 12 most cited ones), from HST to ISO. Table 2, 3, 4 give the same distribution for the years 1999, 2000, and 2001, respectively. These tables show that HST publications have the highest impact for the years 1998, 1999, and 2000, with some strong challenges from Keck, Scuba, and Boomerang, while the impact of new space observatories, like Chandra and XMM-Newton, is clearly visible in 2001.

Our results, although based on a different sample of HIPs, are consistent with the values found by Benn & Sánchez (2001): HST generates 11% of the total citations in the years 1995 to 2001.

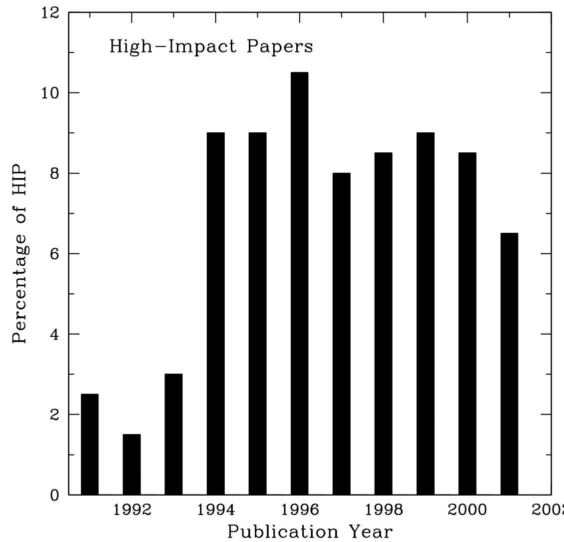


Fig. 7.— Percentage of HST High Impact Papers (HIPs), from the ADS. Since 1994, Hubble has consistently generated about 8% of all observational HIPs.

## 5. Top ten most productive HST programs

Since all 4,116 HST refereed papers are linked in our databases to the programs having generated the data, it is straightforward to identify the most productive programs. Table 5 lists the ten most productive HST programs, in decreasing numbers of related papers. Column 1 provides the program type, Column 2 the Program I.D., Column 3 the P.I. last name, Column 4 the title of the program, Column 5 the number of papers generated, and Column 6 the total number of citations to these papers.

It is worth noting that all program categories are present in this table, with not only General Observer (GO) programs, but also Guaranteed Time Observer (GTO) programs, Parallel (PAR) programs, snapshot (SNAP) programs, and Director Discretionary time (DD) programs. This illustrates the usefulness of each of these program categories. Not surprisingly, the top program is the Hubble Deep Field, with Williams as the PI, which may have produced the most original, broad impact, and far reaching HST scientific results yet.

## 6. Top ten most cited refereed HST publications

The same databases allow the identification of the most cited refereed articles based on Hubble data. Table 6 lists the ten most cited HST papers. Column 1 gives the name of the first author, Column 2 the title of the paper, and Column 3 the bibliographic reference of the paper. These papers are sorted by decreasing numbers of citations, Column 4.

This list of publications contains only papers presenting new scientific results; we have not included instrumental/calibration papers.

## 7. Conclusion

The creation of effective links between the STScI and ADS databases containing information about all HST programs, all HST refereed papers, and their citations, provides us with a powerful and versatile way to obtain metrics about describing the efficiency, productivity, and scientific impact of the Hubble Space Telescope project.

This may certainly help the funding agencies and the various governing committees in shaping the future of HST time allocation through educated decisions. The evaluation of the present performances of space facilities like HST, Chandra and Spitzer will help to maximize the efficiency and scientific output of future projects, like the James Webb Space Telescope (JWST).

This research has made extensive use of the NASA Astrophysics Data System Bibliographic services. We thank the ADS team and specially Michael Kurtz for providing us with numerous data about citations and reads of HST papers. We are grateful to the STScI Librarian, Sarah Stevens-Rayburn, for her invaluable input. Many thanks to the MAST team at STScI, particularly Karen Levay, Paolo Padovani, and Sara Anderson for storing and handling the data used in this study. We are also grateful to Tim de Zeeuw and Don York for useful comments.

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Table 1

ADS High-Impact Papers 1998

| Telescope | Fraction of the Total |
|---|---|
| HST | 13.5 |
| Keck | 7.5 |
| Kamiokande | 6.8 |
| COBE | 6.8 |
| NOAO | 7.1 |
| ROSAT | 5.3 |
| SCUBA/JCMT | 4.7 |
| ASCA | 4.0 |
| Hipparcos | 3.3 |
| ESO | 2.7 |

Table 2

ADS High-Impact Papers 1999

| Telescope | Fraction of the Total |
|---|---|
| HST | 11.8 |
| Keck | 7.6 |
| ROSAT | 7.3 |
| SCUBA/JCMT | 5.3 |
| Kamiokande | 5.1 |
| WHT | 3.2 |
| NOAO | 3.1 |
| ISO | 2.8 |
| ASCA | 2.5 |
| CGRO | 2.4 |

Table 3

ADS High-Impact Papers 2000

| Telescope | Fraction of the Total |
|---|---|
| HST | 12.6 |
| Keck | 11.5 |
| Chandra | 7.7 |
| Boomerang | 5.8 |
| ASCA | 4.6 |
| ESO | 4.1 |
| MAXIMA | 3.8 |
| ISO | 3.4 |
| ROSAT | 3.4 |
| FUSE | 3.4 |

Table 4

ADS High-Impact Papers 2001

| Telescope | Fraction of the Total |
|---|---|
| Chandra | 12.6 |
| XMM-Newton | 11.9 |
| Keck | 9.6 |
| HST | 8.9 |
| ESO | 7.8 |
| AAT | 4.9 |
| MAXIMA | 4.0 |
| NOAO | 3.9 |
| SDSS | 3.6 |
| ROSAT | 2.3 |

Table 5
Top ten most productive programs

| Program Type | Program I.D.[1] | PI | Title | Papers | Citations |
|---|---|---|---|---|---|
| GO/DD | 6337 | Williams | Hubble Deep Field | 119 | 5232 |
| GO/PAR | 5369 | Griffiths | Medium Deep Survey | 88 | 2029 |
| GO | 2424 | Bahcall | Quasar Absorption Line Survey | 58 | 1953 |
| GO | 2227 | Mould | Determination of the Extragalactic Distance Scale | 57 | 2469 |
| SNAP | 5476 | Sparks | 3CR Radio Galaxies | 57 | 719 |
| GO/DD | 8058 | Williams | Hubble Deep Field South | 48 | 772 |
| GTO | 5236 | Westphal | Nuclei of Nearly Normal Galaxies | 48 | 1973 |
| SNAP | 5479 | Malkan | Subarcsecond Structure of AGN | 45 | 485 |
| GO | 2563 | Kirshner | SINS The Supernova Intense Study | 40 | 524 |
| SNAP | 7330 | Mulchaey | The Fueling of Active Nuclei | 40 | 416 |

[1]arge or multicycle programs may acquire different I.D. numbers when scheduled through more than one cycle

Table 6
Top ten most cited HST papers

| First author | Title | Reference | Citations |
|---|---|---|---|
| Madau | High redshift Galaxies in the Hubble Deep Field | 1996, MNRAS, 283, 1388 | 701 |
| Williams | The Hubble Deep Field | 1996, AJ,112, 1335 | 586 |
| Magorrian | The Demography of Massive Dark Objects | 1998, AJ, 115, 2285 | 568 |
| Perlmutter | Discovery of a supernova explosion | 1998, Nature, 391, 51 | 397 |
| Gebhardt | Black Hole Mass and Galaxy Velocity Dispersion | 2000, ApJ, 539, L13 | 378 |
| Freedman | Results from the HST key project to measure $H_0$ | 2001, ApJ, 553, 47 | 370 |
| Freedman | Distance to the Virgo Cluster Galaxy M100 | 1994, Nature, 371, 757 | 301 |
| Stetson | The center of the core-cusp globular cluster | 1994, PASP, 106, 250 | 278 |
| Freedman | The HST Extragalactic Distance Scale | 1994, ApJ, 427, 628 | 271 |
| Lowenthal | Keck Spectroscopy of z$\sim$3 Galaxies in the HDF | 1997, ApJ, 481, 673L | 271 |